Chapter 6. Electromagnetic Phenomena

Objectives: Upon completion of this chapter you will be able to describe in general terms characteristics of natural and artificial emitters of radiation. You will be able to describe bands of the spectrum from DC to gamma rays, and the particular usefulness radio frequencies have for deep-space communication. You will be able to describe the basic principles of spectroscopy, Doppler, reflection and refraction.

Electromagnetic Radiation

Electromagnetic radiation (radio waves, light, etc.) consists of interacting, self-sustaining electric and magnetic fields which propagate through empty space at the speed of 299,792 km per second. Thermocuclear reactions in the cores of stars (including the sun) provide the energy that eventually leaves stars primarily in the form of electromagnetic radiation. These waves cover a wide spectrum of frequencies. Sunshine is a familiar example of electromagnetic radiation that is naturally emitted by the sun. Starlight is the same thing from “suns” that are much farther away.

When a direct current (DC) is applied to a wire (conductor) the current flow builds an electromagnetic field around the wire, propagating a wave outward from the wire. When the current is removed the field collapses, again propagating a wave. If the current is applied and removed repeatedly over a period of time, or if the applied current is made to alternate its polarity with a uniform period of time, a series of waves is propagated at a discrete frequency. This phenomenon is the basis of electromagnetic radiation.

Electromagnetic radiation is propagated nominally in a straight line at the speed of light in a vacuum, and does not require a medium for transmission. It is slowed as it passes through a medium such as air, water, glass, etc. The amount of energy arriving at a detecting device of fixed area located at a given distance from an isotropic source is proportional to the amount of energy passing the surface of an imaginary sphere with a radius of the given distance.

Therefore, the amount of electromagnetic energy passing through a unit area decreases with the square of the distance from the source. This relationship is known as the inverse-square law of (electromagnetic) propagation. It accounts for loss of signal strength over space, called space loss.

The inverse-square law is significant to the exploration of the universe, because it means that the observable electromagnetic radiation decreases very rapidly as the distance from the emitter is increased. Whether the emitter is a spacecraft with a low-power transmitter or an extremely powerful star, it will deliver only a small amount of electromagnetic energy to a detector on Earth because of the very great distances, and the small area that Earth subtends on the huge imaginary sphere.

Recap

1. When a... current is applied to a wire the current flow builds an ____________________ field around the wire propagating a wave outward...
2. If the applied current were made to alternate with a uniform period of time, a series of waves will be propagated at a discrete _______________________ .
3. ...the amount of electromagnetic energy passing through a unit area decreases with the _______________ of the distance from the source.

1. electromagnetic *2. frequency* *3. square*

Electromagnetic Spectrum

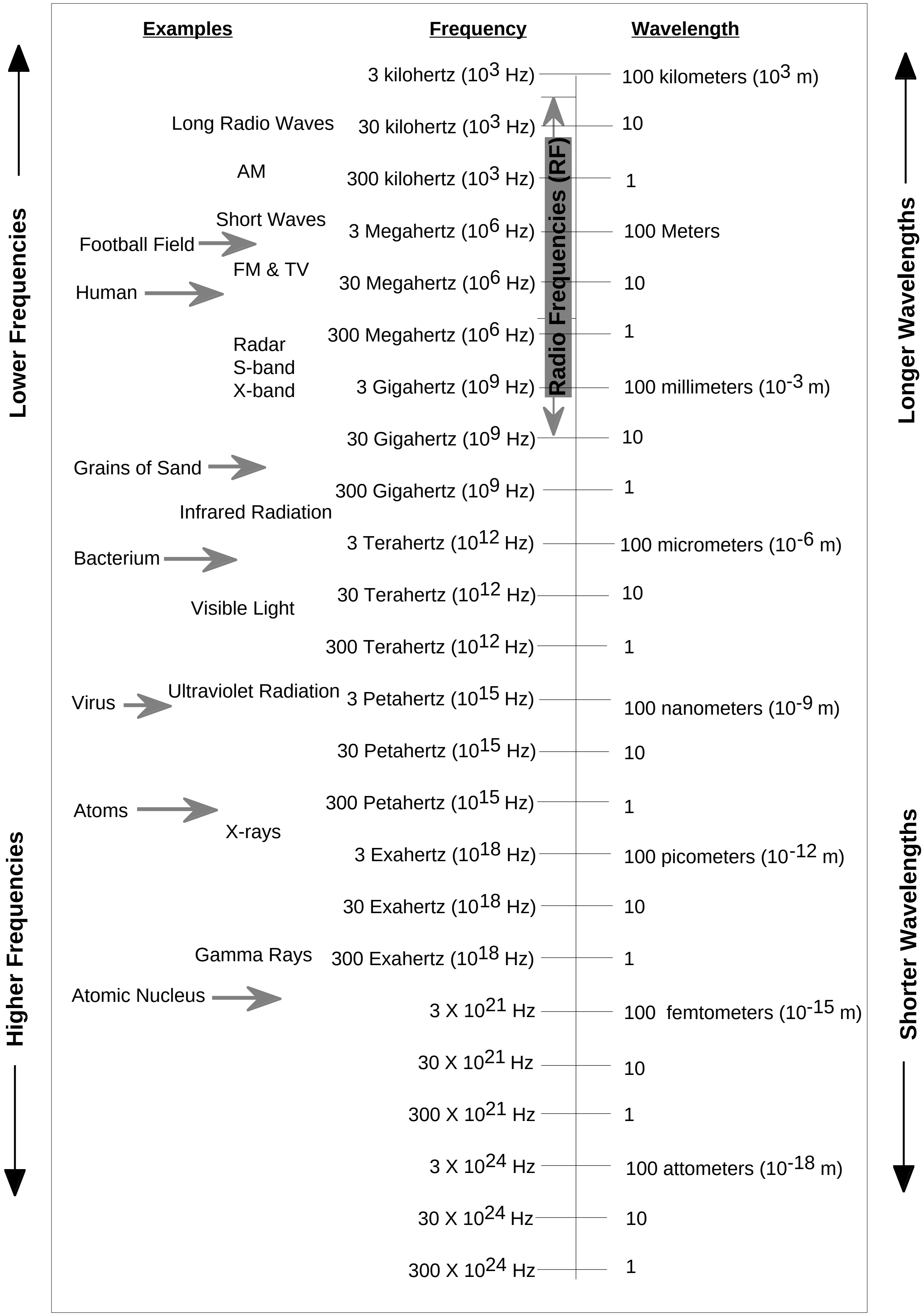
Light is electromagnetic radiation at those frequencies that can be sensed by the human eye. But the electromagnetic spectrum has a much broader range of frequencies than the human eye can detect, including, in order of increasing frequency: radio frequency (RF), infrared (IR, meaning "below red"), light, ultraviolet (UV, meaning "above violet"), X rays, and gamma rays. These designations describe only different frequencies of the same phenomenon: electromagnetic radiation.

The speed of light in a vacuum, 299,792 km per second, is the rate of propagation of all electromagnetic waves. The wavelength of a single oscillation of electro-magnetic radiation is the distance that the wave will propagate during the time required for one oscillation. There is a simple relationship between the frequency and wavelength of electromagnetic energy. Since electromagnetic energy is propagated at the speed of light, the wavelength equals the speed of light divided by the frequency of oscillation.

$$\text{Wavelength} = \frac{\text{Speed of Light}}{\text{Frequency of Oscillation}}$$

$$\text{Frequency of Oscillation} = \frac{\text{Speed of Light}}{\text{Wavelength}}$$

The Electromagnetic Spectrum: Wavelength/frequency chart



Natural and Artificial Emitters

Deep space communication antennas and receivers are capable of detecting many different kinds of natural emitters of electromagnetic radiation, including the stars, the sun, molecular clouds, and gas giant planets such as Jupiter. Although these sources do not emit at truly random frequencies, without sophisticated signal processing, their signals appear as “noise” (pseudo-random frequencies and amplitude). Radio astronomy is the term given to the activities of acquiring and processing electromagnetic radiation from natural emitters. The JPL Deep Space Network (DSN) participates in radio astronomy research.

All deep space vehicles are equipped with radio transmitters and receivers for sending signals (electromagnetic radiation) to and from Earth-based tracking stations. These signals are at pre-established discrete frequencies. Various natural and human-made emitters combine to create a background level of electromagnetic noise from which the spacecraft signals must be detected. The ratio of the signal level to the noise level is known as the signal-to-noise ratio (SNR).

Recap

1. Radio... infrared, light, ultraviolet, X rays, and gamma rays... describe only a difference in frequency of the same phenomenon: ________________________ ________________________ .
2. Since electromagnetic energy is always propagated at the speed of light, the wavelength equals the speed of light divided by the _____________________ .
3. The ratio of the signal level to the noise level is known as the (abbreviation) ___ ___ ___ .

1. electromagnetic radiation 2. frequency 3. SNR

Radio Frequencies

Electromagnetic radiation with frequencies between about 10 kHz and 100 GHz are referred to as radio frequencies (RF). Radio frequencies are divided into groups which have similar characteristics, called “bands,” such as “S-band,” “X-band,” etc. The bands are further divided into small ranges of frequencies called “channels,” some of which are allocated for the use of deep space telecommunications. Many deep-space vehicles use S-band and X-band frequencies which are in the neighborhood of 2 to 10 GHz. These frequencies are among those referred to as microwaves, because their wavelength is short, on the order of centimeters. Deep space telecommunications systems are being developed for use on the even higher frequency K-band.

Band	Range of Wavelengths (cm)	Frequency (GHz)
L	30 - 15	1 - 2
S	15 - 7.5	2 - 4
C	7.5 - 3.75	4 - 8
X	3.75 - 2.4	8 - 12
K	2.4 - 0.75	12 - 40

Note: Band definitions vary slightly among different sources. These are ballpark values.

Spectroscopy

The study of the production, measurement, and interpretation of electromagnetic spectra is known as spectroscopy. This branch of science pertains to space exploration in many different ways. It can provide such diverse information as the chemical composition of an object, the speed of an object's travel, its temperature, and more—information that cannot be gleaned from photographs. Today, spectroscopy deals with closely viewed sections of the electromagnetic spectrum. For purposes of introduction, imagine sunlight passing through a glass prism, casting a bright rainbow (spectrum) onto a piece of paper. Imagine bands of color going from red on the left to violet on the right. Frequencies of the light increase from left to right; the wavelengths decrease. Each band of color is actually a wide range of individual frequencies which cannot be discerned by the human eye, but which are detectable by instruments.

Now, instead of the green band near the middle, imagine a dark band, like a shadow at that point, as if something had absorbed all the green out of the sunlight. Call this a "dark line." What is spoken of as a "bright line" could be imagined as an excessively bright color band, say for example if the green were several times brighter than it normally would appear, as though the sunlight were somehow augmented at this band. In actuality, the bright and dark lines spoken of in spectroscopy are extremely narrow, representing only a very specific shade of color, one discreet frequency at a time. In principle, a bright line represents the emission of radiation at a particular frequency, and a dark line indicates the absorption of a frequency otherwise expected to be seen at that point.

In 1859, Gustav Kirchhoff (1824-1887) described spectroscopy in terms of the three laws of spectral analysis:

I. A luminous (glowing) solid or liquid emits light of all wavelengths (white light), thus producing a continuous spectrum.

II. A rarefied luminous gas emits light whose spectrum shows bright lines (indicating light at specific wavelengths), and sometimes a faint superimposed continuous spectrum.

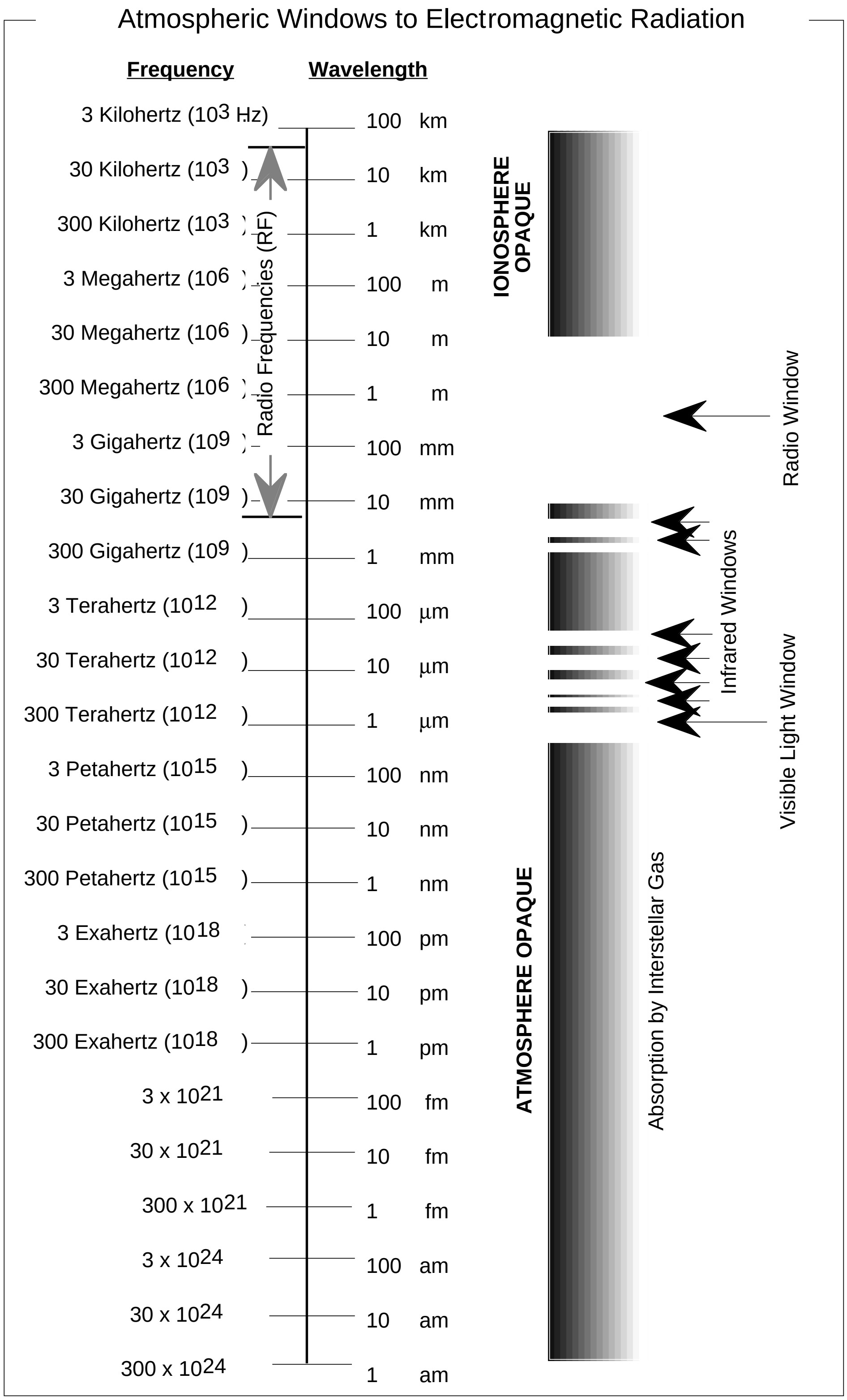
III. If the white light from a luminous source is passed through a gas, the gas may absorb certain wavelengths from the continuous spectrum so that those wavelengths will be missing or diminished in its spectrum, thus producing dark lines.

By studying the bright and dark lines (emission and absorption lines) in the spectra of stars, in the spectra of sunlight reflected off planetary surfaces, or of starlight passing through planetary atmospheres, much can be learned about the composition of these bodies. Historically, spectral observations have taken the form of photographic prints showing spectral bands, in which light and dark lines can be discerned. Modern spectrometers (discussed again under Chapter 12, Typical Science Instruments) have largely done away with the photographic process, producing their high-resolution results in the form of X-Y graphic plots, whose peaks and valleys reveal intensity on the vertical axis versus frequency or wavelength along the horizontal. Peaks of high intensity in this scheme represent bright spectral lines, and troughs of low intensity represent dark lines.

Atmospheric Transparency

Because of the absorption phenomena, observations are impossible at certain wavelengths from the surface of Earth, since they are absorbed by Earth's atmosphere. There are a few "windows" in its absorption characteristics which make it possible to see visible light, and receive radio frequencies, for example, but the atmosphere presents an opaque barrier to much of the electromagnetic spectrum.

Even though the atmosphere is transparent at X-band frequencies as seen above, there is a problem when liquid or solid water is present. Water exhibits noise at X-band frequencies, so precipitation at a receiving site increases the system noise temperature, and this can drive the SNR too low to permit communications reception.


Atmospheric Windows to Electromagnetic Radiation
Frequency
Wavelength
3 Kilohertz (10^3 Hz)
30 Kilohertz (10^3)
300 Kilohertz (10^3)
3 Megahertz (10^6)
30 Megahertz (10^6)
300 Megahertz (10^6)
3 Gigahertz (10^9)
30 Gigahertz (10^9)
300 Gigahertz (10^9)
3 Terahertz (10^12)
30 Terahertz (10^12)
300 Terahertz (10^12)
3 Petahertz (10^15)
30 Petahertz (10^15)
300 Petahertz (10^15)
3 Exahertz (10^18
30 Exahertz (10^18)
300 Exahertz (10^18)
3 x 10^21
30 x 10^21
300 x 10^21
3 x 10^24
30 x 10^24
300 x 10^24
100 km
10 km
1 km
100 m
10 m
1 m
100 mm
10 mm
1 mm
100 µm
10 µm
1 µm
100 nm
10 nm
1 nm
100 pm
10 pm
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100 fm
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Radio Frequencies (RF)
IONOSPHERE OPAQUE
ATMOSPHERE OPAQUE
Radio Window
Infrared Windows
Visible Light Window
Absorption by Interstellar Gas

Radio Frequency Interference

In addition to the natural interference which comes from water at X-band, there may be other sources, such as man-made radio interference. Welding operations on an antenna produce a wide spectrum of radio noise. Many Earth-orbiting spacecraft have strong downlinks near the frequency of signals from deep space. Goldstone Solar System Radar (described further in this chapter) uses a powerful transmitter, which can interfere with reception at a nearby station. Whatever the source of radio frequency interference (RFI), its effect is to increase the noise, thereby decreasing the SNR and making it more difficult, or impossible, to receive valid data from a deep-space craft.

Recap

1. A luminous solid or liquid emits light of all wavelengths, producing a ____________________ spectrum.
2. A luminous gas emits light whose spectrum shows bright lines indicating light emitted at ________________ wavelengths.
3. Gas may absorb certain wavelengths from a continuous spectrum so that those wavelengths will be ______________ or _____________ in its spectrum, producing dark lines.

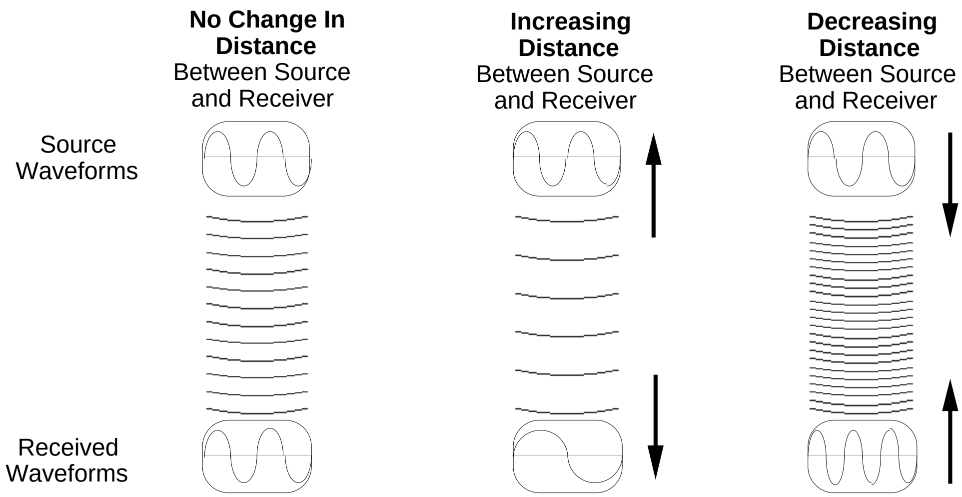
1. continuous 2. specific 3. missing ... diminished

Doppler Effect

Regardless of the frequency of a source of electromagnetic waves, they are subject to the Doppler effect. The Doppler effect causes the observed frequency of a source to differ from the radiated frequency of the source if there is motion that is increasing or decreasing the distance between the source and the observer. The same effect is readily observable as variation in the pitch of sound between a moving source and a stationary observer, or vice-versa.

When the distance between the source and receiver of electromagnetic waves remains constant, the frequency of the source and received wave forms is the same. When the distance between the source and receiver of electromagnetic waves is increasing, the frequency of the received wave forms is lower than the frequency of the source wave form. When the distance is decreasing, the frequency of the received wave form will be higher than the source wave form.

Doppler Effects



The Doppler effect is routinely observed in the frequency of the signals received by ground receiving stations when tracking spacecraft. The increasing or decreasing of distances between the spacecraft and the ground station may be caused by the spacecraft's trajectory, its orbit around a planet, Earth's revolution about the sun, or Earth's daily rotation on its axis. A spacecraft approaching Earth will add a positive frequency bias to the received signal. However, if it flies by Earth, the received Doppler bias will become zero as it passes Earth, and then become negative as the spacecraft moves away from Earth. A spacecraft's revolutions around another planet such as Mars adds alternating positive and negative frequency biases to the received signal, as the spacecraft first moves toward and then away from Earth. Earth's rotation adds a positive frequency bias to the received signal as the spacecraft rises in the east at a particular tracking station, and adds a negative frequency bias to the received signal as the spacecraft sets in the west.

Differenced Doppler

If two widely-separated tracking stations on Earth observe a single spacecraft in orbit about another planet, they will each have a slightly different view, and there will be a slight difference in the amount of Doppler shift observed by each station. For example, if one station has a view exactly edge-on to the spacecraft's orbital plane, the other station would have a view slightly to one side of that plane. Information can be extracted from the differencing of the two received signals that describes the spacecraft's arc through space in three dimensions. This data type, differenced Doppler, is a useful form of navigation data which can yield a very high degree of spatial resolution. It is further discussed in Chapter 13, Spacecraft Navigation.

Recap

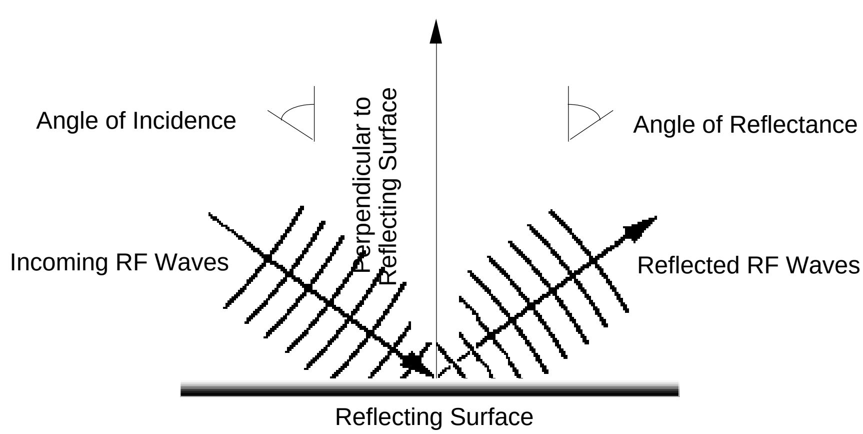
1. The observed frequency of a source will differ from its radiated frequency if there is _______________ which is increasing or decreasing the distance between the source and the observer.
2. When the distance is increasing between the source and receiver of electromagnetic waves, the frequency of the received waves will ______________________.
3. Earth's rotation adds a positive frequency bias to the received signal when the spacecraft rises in the east at a particular tracking station, and adds a _______________ frequency bias to the received signal as the spacecraft sets in the west.

1. motion   2. decrease   3. negative

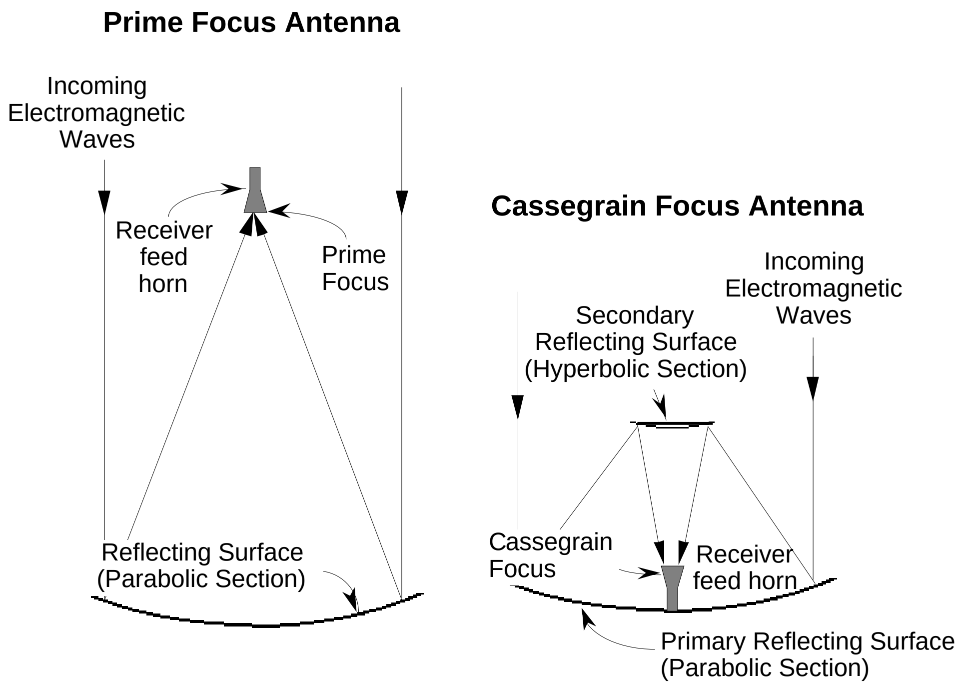
Reflection

RF electromagnetic radiation generally travels through space in a straight line. The exception is that it is bent slightly by the gravitation of large masses in accordance with general relativity. RF waves can be reflected by certain substances, much in the same way that light is reflected by a mirror. The angle at which RF is reflected from a smooth metal surface, for example, will equal the angle at which it approached the surface. In other words, the angle of reflectance of RF waves equals their angle of incidence.

RF Reflected



This principle of RF reflection is used in antenna design to focus transmitted waves into a narrow beam and to collect and concentrate received RF signals for a receiver. If a reflector is designed with the reflecting surface shaped like a paraboloid, electromagnetic waves approaching on-axis will be reflected and will focus above the surface of the reflector at the feed horn. This arrangement is called prime focus, and provides the large aperture necessary to receive very weak signals. The same configuration allows the narrow focusing of signals transmitted from the feed horn, concentrating the transmitted electromagnetic waves into a narrow beam. A major problem with prime focus arrangements for large aperture antennas is that the equipment required at the prime focus is heavy and the supporting structure tends to sag under the weight of the equipment,



thus affecting calibration. A solution is the Cassegrain Focus arrangement. Cassegrain antennas add a secondary reflecting surface to “fold” the electromagnetic waves back to a prime focus near the primary reflector. The DSN’s antennas are of this design because it accommodates large apertures and is structurally strong, allowing bulky equipment to be located nearer the structure’s center of gravity.

The reflective properties of electromagnetic waves have also been used to investigate the planets using a technique called planetary radar. With this technique, electromagnetic waves are transmitted to the planet, where they reflect off the surface of the planet and are received at one or more Earth receiving stations. Using very sophisticated signal processing techniques, the receiving stations dissect and analyze the signal in terms of time, amplitude, phase, and frequency. JPL’s application of this radar technique, called Goldstone Solar System Radar (GSSR), has been used to develop images of the surface features of Venus, eternally covered with clouds, Mercury, difficult to see in the glare of the sun, and some of the satellites of the Jovian planets.

Recap

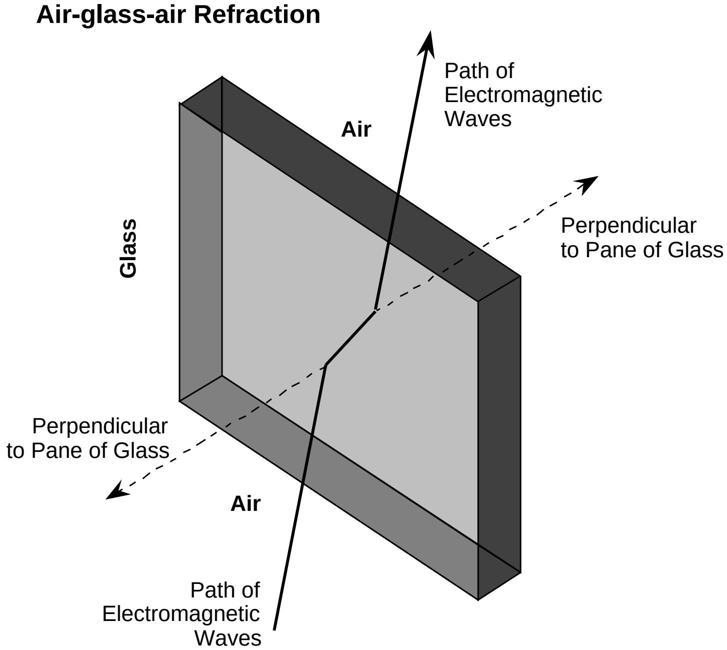
1. Radio frequency electromagnetic radiation generally travels through space in a _______________ ____________ .
2. The angle of reflectance of RF waves equals their angle of _______________ .
3. DSN's antennas are of the Cassegrain design because it accommodates large apertures, and is structurally _______________ allowing bulky equipment to be located nearer the structure's center of gravity.
4. JPL's application of this radar technique, called __________________ ________________ ________________ ________________ (GSSR), has been used to develop images of the surface features of Venus.

1. straight line 2. incidence 3. strong 4. Goldstone Solar System Radar

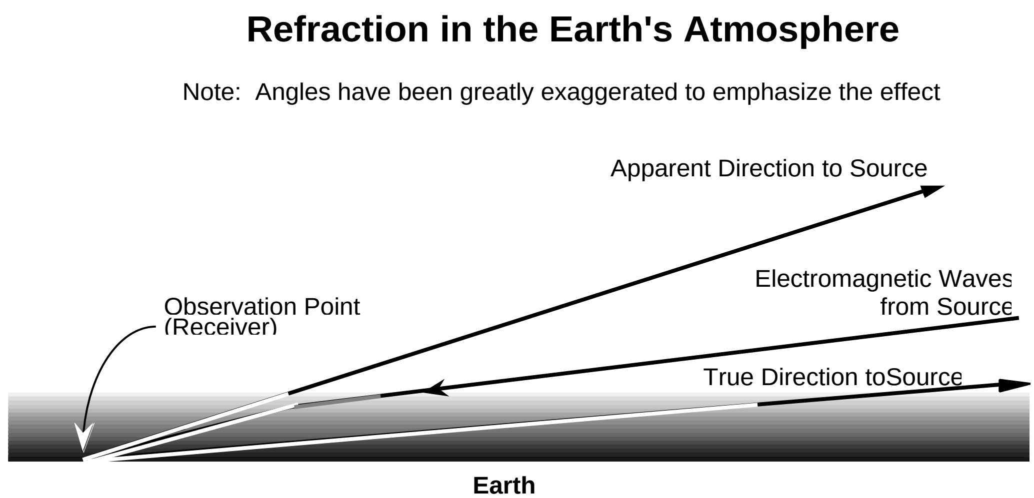
Refraction

Refraction is the deflection or bending of electromagnetic waves when they pass from one kind of transparent medium into another. The index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the substance of the observed medium. The law of refraction states that electromagnetic waves passing from one medium into another (of a differing index of refraction) will be bent in their direction of travel. Air and glass have different indices of refraction. Therefore, the path of electromagnetic waves moving from air to glass at an angle will be bent toward the perpendicular as they travel into the glass. Likewise, the path will be bent to the same extent away from the perpendicular when they exit the other side of glass.

Air-glass-air Refraction



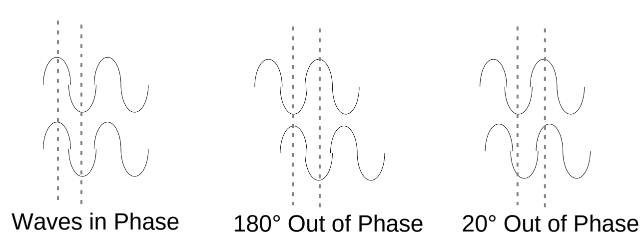
In a similar manner, electromagnetic waves entering Earth's atmosphere from space are slightly bent by refraction. Atmospheric refraction is greatest for signals near the horizon, and cause the apparent altitude of the signal to be on the order of half a degree higher than the true height. As Earth rotates and the object gains altitude, the refraction effect reduces, becoming zero at zenith (directly overhead). Refraction's effect on the sun adds about 5 minutes to the daylight at equatorial latitudes, since it appears higher in the sky than it actually is.



If the signal from a spacecraft goes through the atmosphere of another planet, the signals leaving the spacecraft will be slightly bent by the atmosphere of that planet. This bending will cause occultation (spacecraft moving into a planet's RF shadow of Earth) to occur later than otherwise expected, and exit from occultation will occur prior to when otherwise expected. Ground processing of the received signals reveals the extent of atmospheric bending (and also of absorption at specific frequencies and other modifications), and provides a basis for inferring the composition and structure of a planet's atmosphere.

Phase

As applied to waves of electromagnetic radiation, phase is the relative measure of the alignment of two waveforms of similar frequency. They are said to be in phase if the peaks and troughs of the two waves match up with each other in time. They are said to be out of phase to the extent that they do not match up. Phase is expressed in degrees from 0 to 360.



Recap

1. Refraction is the ___________________ of electromagnetic waves when they pass from one kind of transparent medium into another.
2. The path of electromagnetic waves moving from air to glass at an angle will be bent toward the _____________________ as they travel through the glass.
3. If the signal from a spacecraft goes through the atmosphere of another planet, the signals leaving the spacecraft will be slightly ____________ by the atmosphere of that planet.
4. Waves are said to be in ______________ if their peaks and troughs match up.

1. deflection or bending   2. perpendicular   3. bent   4. phase